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**TECHNICAL DIAGNOSTICS OF MACHINES**

by

**V. P. Lints**

**COUNTRY: USSR**

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# TECHNICAL TRANSLATION

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11

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## Foreword

Machinery diagnostics is a new, rapidly growing branch of machinery science. We have in mind, of course, a scientifically based diagnostics, based on an adequately developed, logical foundation, on fine mathematical and physical methods, permitting optimal results to be achieved. Primitive diagnostics, which comes to a simple search for trouble on a trade level, existed earlier, of course. In this sense, it is the same age as the "Roman chariots" and even more ancient.

An analogy with medical diagnostics suggests itself here, inasmuch as the latter also is occupied with the search for "troubles," only in the human organism. Once upon a time, village wisemen and even physicians were grounded in external or fairly obvious symptoms in the best case, while now fine biochemical and biophysical methods of analysis are taking root more and more widely in medical practice.

Like many new areas of knowledge, machinery diagnostics was born in a joining of different scientific disciplines, among which an important role is played by introscopy, mathematical logic, harmonic analysis, acoustics, radioisotope technology and even psychology.

Since it is so new, as well as because of the exceptional diversity, heterogeneity and complexity of objectives with which it has to do, machinery diagnostics still has not turned into a rigidly formalized system, where any problem can be solved with the help of an exhaustive collection of ready-made algorithms. Personal experience and engineering intuition still are necessary for successful diagnostics.

Above, we defined diagnostics as a branch of machinery science, concerned mainly with the search for defects. Obviously then, their prognoses, as well as automatic defect corrections, can be enumerated here. Diagnostics overall is a part of a more general technical problem, the problem of reliability.

## Diagnostics of Strength and Deformability of Materials and Machine Parts

A part has its place in a machine. If it is properly designed and calculated, the fate of the part and of the entire machine will depend completely on the quality of the material of which they are made.

Previously, there was only one way to obtain information on the strength of materials, destructive tests of specimens. Their results were completely trustworthy, especially if several specimens, taken from different places in the same stock, which afterwards is converted into the assembly of interest to us, are tested simultaneously.

However, all too often it is not possible for an investigator to obtain even one specimen. Frequently, the same type of part is made of stock obtained under different conditions and from different batches of material. To carry out a test in each individual case would be inadmissibly luxurious for any industry. In addition, in many cases, it is necessary to evaluate the reliability of a machine as a whole by checking the reliability of individual parts.

The reader may object that there are statistics. The investigator satisfactorily processes the results of the tests of, for example, a new brand of steel, and has at his disposal information which exhaustively characterizes its properties.

All that is so. But to use this information in calculations, to obtain reliable results by its use, is not so simple. The normal spread in mechanical property indicators is too great. Even in old, widely used brands of steel, on which a gigantic amount of factual material has been accumulated, and which must have had every influence bearing on the results corrected, the maximum yield point is double the minimum, on the average. Now put yourself in the position of a designer receiving such data. In order to be protected from all contingencies, he must introduce the minimum value into calculations. As a result, machines created are substantially "overloaded." Obviously, it would have been tremendously easier if the designer had been in a position to predict the true yield point of specific forgings or castings of which they are made.

With the mechanical properties of such materials as polymers, it becomes still more complicated. They are sensitive to changes in temperature and to the slightest variations in manufacturing procedure. To come to the point, structure of the material never remains constant. Polymerization continues for a long time and aging takes place. Destructive tests of polymer materials, instead of answering the question of properties, present new puzzles. Moreover, in this case, production of the material and production of objects is combined, so that testing has to be, not of specimens, but only of finished parts.

The circumstances enumerated compel a search for new methods of diagnostic evaluation of the strength and rigidity of parts of machines and apparatus.

Defectoscopy is a direct precursor of diagnostics. Its virtue is that both semifinished products and parts themselves can be subject to control. Although the information obtained is not exhaustive, all the same, in the absence of defects, reliable operation of parts can be predicted.

Ultrasound methods are used most often for direct detection of defects in finished units without taking them apart.

Modern ultrasound apparatus has reached a high degree of perfection. Ultrasound defectoscope devices are made up now of transistors and a power source, a compact storage battery, hidden in the apparatus itself. It is light, portable and self-contained.

As a result, it has become possible to evaluate performance reliability of units which previously could not even be made because there was no possibility of such an evaluation. Take modern power engineering. Its development is characterized by sharp increases in pressure, temperature and speed. Here are figures which illustrate the operation of a modern steam boiler, supplying steam to an 800,000 kw turbine: pressure, 255 atm; steam temperature, 565°C; capacity, 2500 tons of steam per hour. "It is not easy to fit" piping which fills the space of housings several tens of stories high. Kilometers of tubing of various diameters are joined in sections, which are joined together in turn. There are thousands of joints, mainly welded, concealing a potential danger of accidents. Until recently, the only guarantee of reliability of joints was the skill of the most highly qualified welders (and only such are permitted to do assembly work on a boiler). A personal brand on every weld testifies to the hand of a master. Of course, such a guarantee is insufficient. One only needs to imagine what even an insignificant defect can become in an instant under the continuous action of the pressure of 250 atm and 600° of head, and it becomes clear that a personal brand is little.

For some section of a huge boiler to go out of order is much too expensive a "pleasure," even when safety procedures prove to be high-level and people are not injured. For the damaged section must be disconnected, the steam dumped and the damage found. In order to find and replace the broken tube, dozens must be cut, including hundreds of meters of "healthy" tubing. Add lost time, boiler performance at only partial power and the lie to this trouble.

Obviously, inspection is necessary. Inspection of welded seams is most necessary of all.

Transistors produced by our radio industry permitted developers from Central Scientific Research Institute of Technology and Mechanical Engineering to create an extremely miniaturized inspection instrument, not yielding to that of a lamp in sensitivity. In addition, use of a self-contained power source instead of switching it into the electric power system led to an increase in precision of measurements. Electric steel in any undertaking, to say nothing of the multiplicity of internal interferences, only aggravates errors of measurement because of voltage instability.

Any ultrasound defectoscope, no matter how good, is worth nothing in itself without a reliable scanner. A piezoelement is used here, in which ultrasound oscillations are excited, and which transmits them to the metal being inspected. The piezoelement is enclosed in an epoxide resin cube. The size of the cube is half that of a matchbox. The working surface of the scanner is placed against a tube. A cylindrical concavity snugly encompasses the tube, insuring the necessary contact.

Ultrasound waves emitted by the piezoelement and reflecting from the opposite wall of the tube, penetrate the area of the weld. The bright green outline of a sound impulse spike glimmers on the circular ground glass screen of the apparatus, which is accurately lined with a millimeter grid. If there is a defect in the search field, a second impulse flashes on the screen. The dimensions of the defect can be judged by the amplitude of the surge.

At the same time, the distance between impulses indicates the position of the defect. However, the inspector does not have to follow the flashes on the screen at all. The developers took care of making his work extremely easy. A groove, simulating a defect of the minimum permissible dimensions, was made on a piece of pipe of the same diameter as the one being tested. The defectoscope is adjusted on it. Then, moving along the tubing, the inspector has only to "listen" to the weld seams. If there proves to be a defect larger than is permitted in the search area, an alarm beep sounds in the head phones. Then, the screen helps to discriminate the finding more in detail.

Ideally, there should be inspection, not only of the welding seams, but of the tubing itself. It would be reasonable to set up inspection of the tubing immediately after its manufacture, upon emergence from the rolling mill. Technical conditions are extremely rigid: 0.6 mm and larger internal and surface defects must be detected without error. In addition, the defectoscopy must be rapid. Otherwise, it would slow down the rolling itself.

It would seem that the use of ultrasound is impossible in this case. A necessary condition for ultrasound inspection is contact of the scanner with the surface of the tubing, which is smeared with oil when it should be clean. The tubing moves with great speed. With the poor fit of the scanner, its rapid wear and tear is unavoidable.

A way out was found by the same developers. They proposed to pass the tubing through a water bath. Water is an ideal medium from the point of view of propagation of ultrasound oscillations.

Initially, the following plan was settled on: the rapidly rotating tubing, with its ends stopped up, goes through the bath, where the scanner is installed so that ultrasound waves encompass the entire surface of the tubing in a spiral. In order to increase the inspection rate, it is necessary to rotate the tubing faster. Otherwise, the pitch of the spiral becomes too great and a defect can be missed.

Research led to another plan: the tubing moves ahead and the scanner rotates. This plan is better, because the expenditure of energy for rotating a small scanner is significantly lower than for rotating heavy tubing. Air bubbles, which do not transmit ultrasound, distort the performance of the apparatus. A special device was introduced to exclude the bubbles from access to the operating zone.

The basis of a new variant is that nothing rotates. Several stationary scanners encircle the tubing, which literally "shoots through" the bath with express train speed. The installation was simplified to an extreme, and far outdistanced all known methods of pipe manufacture in productivity.

The importance of such inspection is obvious, inasmuch as the tubing is the raw material for a great number of mechanical assemblies and parts.

The discovery of a defect in a part promises a disruption of its strength in the near future and is a weighty argument for making a diagnosis. But, here is no back link between the appearance of flaws and defects. In other words, the presence of a defect is not at all certain to result in formation of a crack. This has been confirmed many times in practice. Moreover, cases are encountered in which a defect improves the property of the material. For example, an impurity in a metal sometimes inhibits development of a dislocation, a distortion of its crystal lattice. Introduction of certain impurities into a metal is one of the means of making it stronger.

Materials production is distinguished by continuous improvements in technology. As a result, materials become more uniform, and this means that the probability of appearance of defects decreases. Let us take steel for an example. From time immemorial, every smelting has been poured into casting molds, where the steel solidified in the form of individual ingots. Such a procedure in itself predetermines numerous defects, many of which are not corrected, even in subsequent pressure treatment. Zonal chemical discontinuities always was one of the incorrigible defects. The introduction of continuous casting, when steel is obtained in the form of an endless ingot, a strip, completely corrected this defect.

It will happen that a part in which no defects whatever were detected breaks down. Actually, of course, there are defects, but the inspection apparatus has a limited sensitivity. Well, practically, individual indiscernible defects are not dangerous. The smaller their dimensions, the smaller the probability of breakdown.

However, an accumulation of microdefects, not detected by the defectoscopes, is dangerous. A diagnosis confirming the suitability of the part will be incorrect in this case.

It has been established by numerous experiments that the minimum dimension of an individual defect which can be detected, and which does not affect the strength of the part, is immeasurably larger than the dimensions of

microdefects which appear as various irregularities in the structure of the material. Mechanical properties of a material are a measure of its structure. The denser it is, the stronger the material. The fact is that such facts as, for example, the relationship between changes in strength and rigidity of steel and its hardness, and not only defects, prevail in determining mechanical properties of the material.

Mechanical properties of materials depend on temperature, deformation rate, some radiations and so on and so forth. All of this substantially complicates diagnostics, although it does not make it impossible.

The main thing is to find just those physical characteristics of the material, changes in which immediately would affect its strength and deformation properties. Of course, such connection, also studied initially on specimens by means of numerous tests, must be stable. Only then, having determined the selected physical characteristic directly on the finished part, and not on specimens, can we make a judgement on its carrying capacity.

It must be stipulated that we are taking certain terminological liberties when we speak separately of physical and mechanical properties of a material. After all, rigidity and strength are also physical characteristics, analogous, for example, to electrical conductivity or heat capacity.

However, as is already the rule in engineering, macroscopic behavior of a material characterizes its mechanical properties and the interactions of microparticles, the physical. Actually, in the final analysis, macroscopic processes are a summation of microscopic processes. Therefore, there is a natural tendency to connect theoretical relationships found, which describe the conduct of microparticles, with changes in mechanical properties.

Strength is determined by the force of interactions among elementary particles. It decreases in proportion to an increase in distance between them. Theoretical strength is inversely proportional to the square of the distance between particles. However, in comparison with findings of the normal destructive tests, it turns out to be increased or decreased by several orders of magnitude.

Does this mean that a similar, particularly theoretical, diagnostics must be summarily rejected and that it is necessary to search for a different route? We have no unequivocal answer yet.

In fact, a theory which roughly provides for elementary particles turns out to be too coarse in transposition from them to macroscopic amplitudes. The almost ideal conditions of existence of microparticles in themselves turn out to be disturbed by the imposition of a multiplicity of accompanying circumstances.

It is known that any metal is not a continuous mass, but individual grains or crystals cemented together, as it were. Its own laws operate within each of them. However, crystals form a so-called dendritic structure,

which, if it is examined under magnification, is similar to a coherent tree-like structure. In tree-like structures of various dimensions, they are joined together differently. Moreover, cavities, blisters of air which have gotten into the melt, metallurgical gases and the like can be detected easily on fractures of cast metal among the sparkling facets of the grains, which are aggregations of crystals.

Although ideal relationships, satisfactorily describing behavior of elementary particles, can be maintained for the crystals themselves, correction coefficients, at least, are required for groups of crystals.

Nevertheless, a qualitative image of the relationships mentioned is established. It is difficult to discriminate among the sources of changes in strength and deformation properties of the material without them. But using them, further search for diagnostic means does not need to be conducted blindly.

It is better to use a set of characteristics, and not one physical characteristic, of a material as the criterion for making more accurate predictions of behavior of a part. Strictly speaking, any characteristic is a set in itself, inasmuch as it depends on several properties, and not on one. For example, hardness is determined by elastic and plastic properties, but the dynamic modulus of elasticity can be found from, not only the density of the material, but from the propagation rate of oscillations in it.

For that matter, the more characteristics are drawn on for a prognosis of mechanical properties, the greater the variety of changes in properties of a material that can be taken into account in the prognosis, and the more widely this prognosis can be used.

It is only necessary that the set of characteristics be determined under identical conditions or at least be well known, for controlling characteristics depend on changes in conditions. Otherwise, fixed parameters will depend on many unknowns, and the experiment loses all sense.

It will also happen that different investigators obtain different data on mechanical characteristics of one and the same material, even though they use identical relationships. More than that, such things occur in different experiments by one investigator. The reason is most often found in the material itself, or to be more precise, in the conditions of its manufacture. Material quality does not only depend on how strictly the procedures are followed. Sometimes, the time of year and even the day it is manufactured is of importance. Therefore, before beginning diagnostic tests of a machine part, known information on the conditions of "birth" of the material are required.

Destructive tests cannot be dispensed with in diagnostics, inasmuch as a so-called calibration graph should be plotted to begin with, that is,

the relationship between physical and mechanical characteristics. This is done as follows.

The necessary physical characteristics (for example, heat and electrical conductivity, propagation rate of oscillations and the like) are determined on specimens of the material. Then, the same specimens are subjected to destructive testing, which reveals their mechanical properties. Then, a calibration curve can be plotted. Having determined the physical characteristics of a material directly on a finished part, its mechanical characteristics are found by use of such curves.

Intensive research being conducted in these little-studied fields, in which connections between physical and mechanical properties are established, are of great interest and, sometimes, lead to completely unexpected results.

One of the most "popular" and easily measured characteristics of any material is its electrical resistance. A group of colleagues of the Moscow Engineering Physics Institute, under the direction of Doctor of Technical Sciences D. Skorov and candidate in technical sciences V. Maskal'ets, were occupied, for example, in a study of how the resistance of cast beryllium changes under compression. The investigators invented a new method of determining strength as a result.

The increased brittleness of beryllium compared with other materials made any disruption of the integrity of a specimen evident. The investigators did this: each time, before the beginning of an experiment, in installing a specimen, a small cylindrical stick, in a loading device, they assured themselves with their own eyes of the absence of any kind of damage.

The compression force was created in the device by rotating a horizontally situated screw and was transmitted to the specimen through a so-called indenter, a small cylindrical molybdenum rod. The end of the indenter making contact with the specimen was rounded, inasmuch as the investigators attempted to avoid concentration of the load as much as possible. Of course, they insulated the loading device from the parts, in order that the specimen being tested and the indenter might be used as elements in an electrical circuit.

The potentiometric circuit was most sensitive to the slightest change in resistance. Contact between the indenter and the specimen closed it. The investigators measured the resistance at the point of contact and increased the load by turning the screw handwheel. The circuit resistance smoothly decreased in proportion to the pressurizing of the specimen. This was logical. As the indenter pressed into the specimen, the area of contact between them increased and the conducting surface became larger. The current path previously squeezed into a narrow beam, acquired relative spaciousness. Suddenly, contrary to all logic, after the next increment of force, the line of the graph changed direction, jumping up. The resistance increased.

Repeated experiments recorded the repetition of this phenomenon, which is seemingly inexplicable. Beginning at a definite force, the straight line of the graph changed to a broken one. An increase in resistance alternated with a decrease. A metallographic study showed that a web of microfissures started next to the edges of the contact area. All at once, everything fell into place. The fissures changed the dimensions of the contact area and disrupted the migration of electrons, which was reflected immediately in an increase in resistance.

It is interesting that the fissures arose just where they should have arisen, proceeding from pure theoretical considerations on the loading state at the point of contact. Theory and experiment agreed that disruption must occur at the edge of the area where the tensile stress reached a maximum.

Thus, unexpectedly, a new method of investigation of the strength of materials appeared.

To digress a little, we notice that one of the virtues of the new method is that it enriches the standard methods of destructive testing. How is the formation of the first cracks really fixed in fatigue testing? No one knew this before now. Periodically inspecting specimens or parts removed from the testing machine, the investigators could determine at best that the cracks appeared sometime between so many and so many millions of cycles. Now, for the first time, an abrupt change in resistance permits precise recording of the moment of appearance of the first cracks. It is entirely possible that the use of this method will not be limited to specimens in the future. It might be suggested that suspicious parts will be connected to the circuit and diagnosis made of them on the basis of measurement of circuit resistance.

It is difficult to predict now all the possibilities which investigators will produce with the appearance of the "method of study of initial stages of disruption of solid bodies" (this is its official name). New possibilities will be uncovered at every turn of the road followed by development and use of this method.

If a part is made of a dielectric material, a diagnosis is made by evaluation of its dielectric constant or dielectric phase loss angle. The first characterizes change in the strength of point charge interactions, and the second indicates how much energy must be consumed in dielectric heating. Both indicators are determined by the structure of the material in particular. Therefore, they can be used as a diagnostic means, because the slightest changes in structure under the influence of defects, impurities, temperature of the surroundings and the like directly affect the electrical properties. Some of the factors enumerated act with a "plus" sign and others with a "minus" sign. The conditions under which testing is carried out are important also (for example, moisture affects electrical conductivity). In short, diagnostics based on testing the electrical properties of the material is fairly capricious. Changes

in these properties cannot always be connected with strength and deformation characteristics of the material alone.

Further, it is known that the reason for thermal expansion of materials is the weakening of the interacting forces between elementary particles, due to increase in amplitude of their oscillations with increase in temperature. Thermal conductivity of nonmetals, for example, is explained by scattering of heat waves in those places where the material is not uniform. In metals, it is dependent upon electron conductivity, confirmation of which is its decrease under the action of an electromagnetic field.

The relation connecting the coefficients of thermal conductivity and linear expansion with characteristic mechanical properties can be derived. In particular, the coefficient of linear expansion is inversely proportional to the distance between particles at equilibrium and the square of the modulus of elasticity.

Contemporary thermodynamics establishes the relationship between electrical and thermal properties of materials and their elasticity at the level of crystals, but these relationships turn out to be inaccurate for larger organizations of materials. It is possible that diagnosis of strength and deformability on this basis will spread in the future, but the most adequate methods today are based on the connection between material properties and wave processes excited in them.

Remember how potters and glass blowers evaluate their products, by the duration of the sound and the pitch and purity of its tone after striking it. But this is only a qualitative evaluation, based on trade practices, experience and intuition. Quantitative indices are required for evaluation of the reliability of machine parts.

A special apparatus, operating with high accuracy, is used for this purpose today. The modulus of elasticity and the shear modulus can be determined by the proper frequency of oscillation of the part, and the Poisson coefficient from them.

Oscillations excited in a material are gradually attenuated. Their energy is absorbed differently, depending on the strength, and thus, the mechanical properties of the material. Attenuation of oscillations is characterized by a special indicator, the logarithmic decrement of attenuation. It is the logarithm of the relative amplitude of two successive oscillations. It can be expressed differently, as the half coefficient of absorption, equal to the relative loss in intensity of oscillatory energy in one period of oscillation.

The proper frequency of oscillation and attenuation decrement in machine parts are determined by special instruments. A sinusoidal voltage produced by a generator is converted into mechanical oscillations in the part being inspected. These oscillations are again converted into electrical ones through a receiver in contact with the part. They can be seen on a cathode-ray tube screen after amplification.

The concordance between the proper frequency of oscillation of the part and the frequency of the excited oscillation is fixed by the maximum deviation of the beam. The attenuation decrement can be determined by the width of the resonance curve peak, expressed in terms of the frequency of proper oscillation and the frequency of oscillation corresponding to half the maximum amplitudes before and after resonance.

Not only the proper oscillation of a part, but extraneous ones, can be used for diagnostics. They propagate differently in parts of different dimensions and materials. Such characteristic elastic properties as the modulus of elasticity and the Poisson coefficient can be determined from the rate of propagation of waves.

The amplitude of oscillations gradually decreases as a consequence of internal friction, nonuniformities in materials and so forth. The so-called coefficient of attenuation (considering attenuation over some distance within the part, beginning with the point of introduction of the oscillation impulse) serves as an indicator of this decrease. The coefficient is proportional to the logarithm of the ratio of the initial amplitude to the amplitude after passing through the section being considered. Of course, this most structurally sensitive characteristic is also used in diagnostics.

Introduction of extraneous oscillations (for example, ultrasound) into the part is used in those cases when a detailed examination of some part of it is required (the resonance methods are used for evaluation of the properties of the part as a whole). Here, it is not compulsory to have access to the part from two sides. The probe of the ultrasound instrument is satisfactorily applied to one side, which is particularly important in the diagnosis of heavy parts.

Steel is one of the most widespread materials for machine parts. Its qualities and properties are determined by the structure and dimensions of the grains. Grain dimensions are evaluated on a ten-point scale according to the All-Union State Standard. For example, three- to eight-point grain steel is used for boiler tubing.

It has been established that grain dimension affects the degree of attenuation of ultrasound oscillations. The larger the grain, the more poorly ultrasound is transmitted. The idea of measuring grains by ultrasound arose from this. This is much simpler than X-ray structural analysis and other traditional methods of metallographic examination.

Inventors V. I. Ryk and V. F. Grebennik, embodying the idea in a working apparatus which they call an "ultrasound structural analyzer," expect that grain dimension can be determined with an accuracy of one point by means of ultrasound. Such a precise diagnostic test substantially increases the reliability of the corresponding boiler assemblies.

## Diagnostic Modeling

Trouble-free operation of any machine is determined for the most part by the rationality of its design. However, even when the design is carefully worked out, maladjustments arising in diagnosis by no means make experimental verification of one or another unit or part, from the point of view of proper accomplishment of their functions, superfluous. If the design is original and unusual, comprehensive experiments are all the more necessary in the process of creating it, in order to guarantee its reliability.

Modern experimental technique can astonish the richest imagination. Take wind tunnels as an example, in which new types of aircraft are scrupulously studied before they are put into production. The tunnel dimensions are so large that they can hold entire aircraft. Garlands of high-accuracy electronic instruments record the stress condition at hundreds of points on the structure at various temperatures and static and dynamic loadings. The practices and methods of experimental reliability are a whole science, with its own laws and traditions, which no purely theoretical discipline exceeds in complexity. It is best of all of course, when an investigator has test specimens of machines of natural size at hand. Thus, test samples of aircraft are reduced to destruction on special test beds, in order to determine the true safety factors. Then, before the beginning of mass production, the resources of the machine are made apparent on pilot models, thereby evaluating its reliability. Subsequently, the results of these laborious operations serve as invaluable material for diagnostics.

The novel of the American science fiction writer, M. Keydin, "Marooned," tells how a space ship turned out to have lost the possibility of returning to earth because of a breakdown in the braking system. The first thing which was undertaken in searching for the trouble was a very thorough analysis of a copy of the space ship remaining on earth.

Before production of a new model of automobile begins, a test model of it is made to go thousands of kilometers on highways and country roads, in mountains and deserts, through snow and swamps. Data of full-scale tests are the most reliable, since the machines are tested in just those conditions under which they are intended to operate.

However, frequently, particularly in diagnostics, the conduct of full-scale tests turns out to be impossible because of operating damages from a great many causes. Then, resort is had to modeling.

In point of fact, a model is a reduction and simplification of the machine itself. The problem of reducing the dimensions while maintaining the reliability and rigidity of the modeled structure is resolved by the so-called similarity theory. It solves questions of accuracy of reproduction in modeling by various processes, which appear in operation of the machine in one way or another. For example, in investigating the streamlining of a body in liquid or gas, constancy of the Reynolds number, which interconnects the linear dimensions, current speed and viscosity of the medium, has to be

insured, in addition to geometrical similarity. It is difficult to maintain this condition. If the same medium is used in modeling as in nature, the current speed should be increased (dimensions of the model are smaller). Increase in speed may produce phenomena which are practically absent at low speeds: cavitation, heating and the like. In the final analysis, the process studied can change beyond recognition...

Inasmuch as it is more convenient to work with a small model, investigators attempt to make its dimensions as small as possible. Such an effort generates difficulties in making a model. Many of its details become invisible in reduction. Therefore, the result is that the model is not always an exact copy of the machine. It is not so much the externals as resemblance in principle that is important to the investigator. Everything secondary, everything which does not have an effect on the aspect of operation of the construction studied, is mercilessly discarded.

One can go still further in everyday diagnostic practice. If it is evident that the reason for a breakdown or malfunction is concealed in some definite place in the structure, is it necessary to reproduce the structure completely? Of course not. The examination can be limited to individual units, parts or even elements of parts, in this case. This is easier and cheaper. Then models appear, the original of which is rarely guessed from the external likeness. These "friendly jokes" on nature are called local models.

For example, clutches are widespread in machines for the most diverse purposes. This clutch must transmit rotation from one shaft to another at a specific moment. The structure of a clutch is uncomplicated. A collar with external cogs is fitted on the first shaft, and the other shaft has a cogged ring on the end. The cogs of the shaft fit the spaces between the cogs of the ring, and then both shafts rotate as one.

Clutches operate under difficult conditions and get out of order much quicker than is desirable. In order to reveal the possibilities for prolonging the service life of clutches, it is necessary to know how each cog is loaded, and how the load is distributed among the individual cogs.

Thus, two models are usually made in tests, each of which only remotely resembles the prototype being investigated. All but three teeth are removed on the first model, two of which have the edges filed down. The torque is transmitted by one tooth which here takes up the given load completely. The second model represents the distribution of the load among the cogs. It is almost like an actual clutch. Almost, because there are no secondary details on it, but then there is an addition, in the middle section, of an insert of optically active plastic. The portion of the load going through each cog can be precisely determined by shining polarized light on it.

Here is another example. The loading of a steel pouring ladle was tested in one of the experiments on two models. The first disclosed a

picture of the load near the trunnions on which the ladle was suspended, and the second demonstrated the interaction between the rigidity of the collar and the wall of the ladle.

Although local models are simpler in structure than universal models, the route to them is very likely more complicated. It begins with a thorough analysis of the structure being studied. It is gone through mentally, unit by unit and part by part. Check calculations are made over and over, probing for weak spots. The degree of reliability of the calculations are evaluated again and again.

When the list of "blank spaces" is ready, a model of them can be designed. The outward form of a model, as we have seen in the example of the clutch, to a great extent, determines the conditions under which the modeled part operates.

Modeling of a whole series of processes can be done without their physical reproduction. It is sufficient for there to be a mathematical congruity between a process and its model. If an equation for movement of an automobile, speeding over a rough road, is written and, beside it, an equation for changes in current strength and voltage in a given electrical circuit, we are easily convinced that they are identical.

Many problems in machine diagnostics can be solved relatively quickly and with acceptable reliability by a mathematical analogy. Diffusion of gases, flow of a liquid, oscillatory processes in machines and many other things can be studied on electrical models, assembled from resistors, condensers and induction coils.

#### Contact Stresses and Plastic Deformations

The unexpected malfunctioning of assemblies and parts is frequently due to an inaccurate presentation of the active loads and stresses, among which contact pressures, which are given poorly by the usual calculations, occupy a special place. The question of how they are distributed among the contact surfaces of machine parts remains unanswered most often. One of two things is usually assumed in evaluating their magnitudes. Either the load on the structure being examined is evenly distributed across the contact surfaces or the load is concentrated in one spot, at a point.

Of course, it will actually happen this way, but, all the same, the load will be something between the first and the second in the majority of cases. In assuming the first, we risk weakening the structure, and introducing the second assumption into the calculation scheme, we risk making it overheavy. The designer strikes a balance between the extremes in which the accuracy of the solution arrived at can never be verified.

The problem of calculations of parts of machines on which the load changes during the operating cycle is still more indefinite. Which of the changing forces and which moment are the most dangerous?

Information on the magnitude and distribution of contact pressures can be decisive in establishing a diagnosis of a breakdown. The necessity for development of some simple and generally acceptable methods of measurement arose long ago.

In principle, the magnitude of the contact pressures can be judged according to the thickness of an insert placed between the contact surfaces. There is a sufficiently strict correlation between the thickness of the insert and the contact stresses exerted on it. However, a material with incompatible properties is required for the insert. It must be strong and easily deformed. The insert must be as thin as possible; otherwise, the picture of the contact pressures is distorted. Together with this, it must remain intact after the action of the load. Deformation of this very thin insert is sufficiently great that it can be measured. Finally, elastic deformation of the bodies in contact themselves, arising under stress, interferes. The insert proves to be thicker in the region of maximum pressure than might have been supposed.

For lack of something better, it is the practice to use carbon measuring gauges to measure contact pressures. A carbon rod, the basic part of such a load cell, changes its electrical resistance under compression. The cylindrical body of the load cell is imbedded in a hole drilled in the surface being studied.

Investigators actually can measure contact pressures at any point on contiguous surfaces by use of carbon load cells. However, there is no solid assurance that the measured pressure and the pressure acting on a surface, not damaged by load cells, have one and the same value and identical distribution. Drilling can substantially change the initial picture. The diagnostic method, in which the assembly or part studied is damaged, is practically inapplicable to actual operating conditions.

Load cells with wire sensors are simpler to manipulate than those with carbon, but holes must be drilled in the contact surfaces as before.

Many efforts have been made to get rid of load cells. However, up until recently, no universal means of any kind has succeeded.

It is true that there is one method, which is fairly reliable after all, which permits a confident judgment of volumetric stress conditions in the arsenal of measuring means with which technicians in experimental determination of stress and deformation are provided. The question concerns so-called photoelasticity. Models of parts being studied, made of special plastics, refract polarized light beams directed towards them in a special manner and shine with unusual color stress patterns. However, the necessity of preparing models, difficulties in modeling friction conditions on the contact surfaces and considerable complexity in treatment of experimental data for determination of contact stresses limit the use of this method. Every institute, to say nothing of factory, does not have its own polarizing-optical equipment.

There comes a moment in the development of any area of research when, after all complications in solutions caused by attempts to establish some sort of ideal, the search begins all over again in a blank space. The invention of Doctor of Technical Sciences M. Tennenbaum faced such a critical moment in the field we are describing. Opportunely, it can serve as an example of the fact that the contact problem sometimes arises under completely unexpected circumstances. While investigating the operation of a potato harvesting combine, it was necessary to follow the behavior of individual tubers. What takes place when they collide with each other and with working parts of the combine? This could be done only by learning somehow to mark each tuber. But how and with what?

M. Tennenbaum decided to wrap the potatoes in pieces of polyethylene film. The fact is that, as a result of deformation and subsequent illumination with polarized beams, the colorless surface of the film was tinted in patterns similar to those arising in models made of optically active material.

The experiment succeeded. The light patterns on the film told of the nature of the contact, gave an idea of the magnitude of the forces and then what the potatoes interacted with... But the importance of the experiment went beyond his frame of reference. Henceforth, in using the polarizing-optical method for diagnostics in the study of contact stresses, it was not compulsory to make volumetric models. It sufficed to introduce film between the surfaces studied, which can be done under practically any conditions, including testing of the most critical and unique assemblies in production.

However, in other respects, excepting the fact itself of the use of film, this is the photoelasticity method all the same, with all its complexities. The complex set-up is required for interpretation of results, and, in order to interpret, the film must be "frozen." Otherwise, the stress patterns disappear as soon as the stress is removed. The film retains patterns only after plastic deformations without "freezing," but in no way after elastic ones.

To evaluate contact stresses arising from the quantitative point of view also was difficult, the more so that deformation of the insert was hampered in the center of the contact surface, and it was not simple to decide what takes place, a decrease or an increase in contact pressures.

Thus, here is a thin insert as the measuring element. The contact stress is evaluated, not by measurement of the thickness of the insert at various points, but by its translucence.

Another approach to the problem was chosen by a group of colleagues of the All-Union Scientific Research Institute of Metallurgical Mechanical Engineering, to which the author belonged. Although a thin insert also figured here as a sensor, it was made of a completely different "test."

...Tracks left on the snow by opalescent reflections of the sun on a cold winter day, tracks on the asphalt pavement floating in the hot summertime, impressions of seals stamped on documents and postmarks on envelopes and postcards... A simple, familiar relation: the stronger the pressure, the clearer, the more in relief the imprint. But it is not only the force that makes the imprint what it is. The material receiving the pressure does not play a secondary role.

If a method is found for discounting the pliancy of the material, then the active force, including the force on a unit area at different points on it, that, is, the contact stress, can be judged by the nature of the imprint.

It is necessary only to obtain imprints on the same material under the action of previously known pressures at the same time, that, is, to conduct a calibration, and to compare them with an imprint appearing under the pressure of an unknown force.

Interleaved sheets of carbon paper and writing paper are placed between steel slabs and put into a press. The zones of action of various pressures are clearly traced on the imprint. In the center, the carbon paper is transformed into regular cigarette paper. It becomes completely transparent, and a black spot spreads on the writing paper, almost like a blot, only with diffuse, gradually lightening edges, passing over to the carbon black of the untouched blackness of the carbon paper and the snowy white of the paper which the carbon paper did not come into contact with. It is not as pretty as polyethylene film under transmitted polarized light; however, it is even more graphic.

However, quantitative evaluation is necessary in addition to qualitative.

In order to obtain it, a pencil of light from an ordinary electric lamp is focused and passes through the imprint onto a photoelement. We observe the desired quantitative result on the scale of a galvanometer connected to the photoelement. A simple loading attachment, two metallic cylinders, moving in a special ring, permit translation of the results obtained from the "language" of electricity to the "language" of mechanics.

A laboratory press gives a gradually increasing force, and imprints, in the form of small circles with an area of one square centimeter, appear on paper strips fed between the cylinders of the attachment. Each of them denotes a contact stress of a specific magnitude. The dimensions of the circle correspond to the cross-section of that beam of light which subsequently goes through the paper and falls on the photoelement objective.

The calibration curve (by the way, it more nearly resembles a straight line and begins to bend only at contact pressures of about  $4000 \text{ kg/cm}^2$ ) is the "dictionary" by use of which the data obtained is interpreted.

As of now, various brands of carbon paper have been tested, the best combinations of carbon paper and writing, drawing and other papers have

been selected for measurement of stresses over various value ranges, the effect of aging of carbon paper on errors in measurements (the oil impregnated with dye evaporates with time, it dries out and easily flakes off) has been studied, and how qualitative analysis of the contact surfaces influences errors in measurement. It has been established that the paper which stays clean in treatment to the greatest extent is V4. It is true that the contact surfaces of the calibration device work all the better with the same cleanliness as the contact surfaces in the experiment. However, the main conclusion is that the paper insert absolutely does not distort the picture of contact stresses. The thickness of one sheet is on the order of 30  $\mu\text{m}$  and thickness of two or three sheets, consequently, does not exceed 100  $\mu\text{m}$ . The elastic properties of the paper, combined with insignificant thickness, make its deformation incommensurably small compared with deformations of even thin metallic plates.

The total measurement error, calculated statistically (triple root mean square) does not exceed 10%, even at high contact stresses, that is, in that section of the calibration graph where the curve begins to bend.

However, satisfactory results have been obtained up until now while working with a calibration attachment, with a different kind of square plates of small dimensions. There was a transition to parts tests, not only under contact stresses, but under other kinds of stress (for example, bending). In other words, we find ourselves in complex stress conditions, in which everything is changed. Summing up the contact stress values obtained by imprint area, we obtained a value greatly exceeding the actual force, which was known precisely.

It turned out that the entire cause was shearing action. When the stressed parts were tested only for compression deformation, everything was all right. As soon as horizontal deformations, in the plane of contact, appeared, the carbon paper reacted to them.

But why is carbon paper necessary? Does the pressure really have no other consequences than removal of the carbon paper pigment layer?

Using regular writing paper, which was impregnated with mineral oil after the pressure was released to increase its transparency, the magnitude of the contact stresses at different points on the contact surfaces was measured again. The paper turned out to be insensitive to shearing actions. The accuracy of measurement was a little less here than with the use of carbon paper (the error amounted to 15% on the average). A method of using carbon paper in the presence of shearing action was found after all.

The new method was successfully tested on operating machines, including stamping presses developing forces on the order of tens of thousands of tons.

A different way of using the imprint method is being developed at the present time. In particular, the question of measuring forces and contact stresses under high temperature conditions is being solved. For this purpose,

the authors chose to use paper withstanding temperatures of up to 600°C, created by the Soviet inventor L. Venchunas.

Contact stresses, to the measurement of which so much effort has been devoted, really are interesting, not in themselves, but as the cause of the appearance of deformations. In the final analysis, it is precisely deformations which are the true culprits in destructions, independent of what stresses and actions on elements of a structure they appear as a result of. Of course, elastic deformations are permissible, whereas plastic, irreversible form changes are a reliable diagnostic symptom which foretells malfunction. The so-called grid method is normally used in investigations of plastic deformations. Straight, mutually perpendicular lines are drawn on the surface of the specimen. Qualitative and even quantitative measures of residual deformations can be discerned in the distortions sustained by the grid after stress on the specimen.

However, the grid method is not suitable for study of behavior of a machine part. Only large deformations, of not less than 5%, can be discriminated by its use, and this is too much. Appearance of such deformations in a machine would signal an emergency situation.

A new method of analysis has appeared comparatively recently. It is akin to the grid method, but with incomparably greater possibilities and, then, with a wider range of application. Basically, the method is the moiré effect, a spontaneous play of light and shadow which appears before the eyes when, moving or turning, networks of parallel lines, concentric circles, points or any other geometric formations are placed one on another.

Inasmuch as human eyes have a limited resolving power, they do not distinguish the successive light and dark lines in measuring distances between them. Only a gray field is visible, with greater or lesser intensity of darkening, depending on which lines predominate, the white or the dark.

Investigating the mechanism of the appearance of moiré stripes in the simplest case, in superimposing grids of parallel lines, it can be noted that the center of the light moiré bands coincides with the place where the light lines of both grids coincide. The center of the dark bands coincides with the place where the dark lines of one grid cover the light lines of the other. Light intensity continually changes from the dark bands to the light ones, depending on the extent to which the light lines of one or another grid are uncovered. In other words, light intensity depends on the ratio of widths of light and dark lines of the grids.

The principal condition for obtaining moiré is that the grid frequency be less than the frequency of the light waves. The moiré effect is a relationship of complex oscillations. The wave lengths of the accumulating oscillations play a role in the spacing of the lines of the superimposed grids, and the wave lengths of the resulting oscillations, in the spacing of the moiré bands.

The astonishing property of moiré bands of magnifying images and movement had already been noted in the last century. When, in our time, the making of fine and accurate networks was learned, moiré began to be used for the measurement of lengths, angles and movements, for testing the qualities of objects, in crystallography, for textile industry needs and so forth. Moiré expanded the possibilities of the electron microscope, permitting observation of, for example, the structure of crystals many times smaller than could be seen through the microscope in itself.

In order to detect deformations of machine parts by use of the moiré effect, grids are drawn on them, which, for example, are photographed before and after loading. Then these grids are superimposed one on another. In superimposing them, a graphic picture of the distribution of deformations arises.

The method of measuring by means of the moiré effect is very much like the polarization-optical method, but is distinguished from it by its purely geometrical nature and independence of the physical properties of the material.

Moiré images permit the measurement of both elastic and residual deformations. However, if elastic deformations can be analysed by other methods, the moiré effect is irreplaceable for residual. It is used for tracing various properties of the material in the plastic range during creep (for example, for analysis of change in the Poisson coefficient). Creep can be observed over time if a movie camera is used. The duration of a measurement has no effect at all on a moiré image.

Grids are made most often by use of phototechniques. The surface of a part is covered with a light-sensitive material (varnish or emulsion) and, after it dries, a grid is imprinted by the contact method.

If the grid is chrome plated or covered with a layer of copper, it can be used at high temperatures. The grid is sometimes etched on the surface of the part with acid for this purpose.

Moreover, the grid does not always have to be imprinted on the part being studied. When experimental conditions permit, an image of the grid can be projected on the surface of the part like on a movie screen. The superimposed grid images show the deformations occurring before and during loading or before and after loading.

Generally speaking, there are fairly many methods of applying a grid. A grid image can be printed on film, which is stuck to a part with the emulsion down, and then removed from the emulsion. Such grids can be dense. Room can be found for forty to fifty lines in one millimeter. And the denser the grid, the more precise the measurement. However, for measurement of spacing, the distance between neighboring lines, a microscope is necessary.

Even higher precision can be achieved by resorting to one trick. Make the spacing of a calibrating grid, that is, one which does not deform, different than the spacing of the grid applied to the part being inspected. Then, the investigator has to do with two, not one, pictures of the moiré bands after deformation. The first of them is obtained after superposition of the calibrating and operating grids before deformation. The true deformation can be determined by subtracting the initial "deformation," found as a result of the superposition of the reference and undeformed grids, from the deformation, found by the moiré image in superposition of the reference and deformed grids.

In this case, the spacing of the moiré bands after deformation must become larger. Therefore, when stretching is analyzed, the spacing of the reference grid must be smaller than the spacing of the operating grid, and in compression, the reverse.

The moiré effect can be used in measuring stress and deformation, not only over the entire surface of the part, but at individual points on it, as is done by use of wire strain gauges. Moiré strain gauges are small-dimension grids superimposed one on another. The lower one deforms with the part, and the upper one is free (they are superimposed in the measurement process).

#### Thermal Indication of Trouble

An unexpected temperature increase or decrease is one of the obvious symptoms of trouble, be it in a human organism, a central heating set or an electric motor winding.

The first who made efforts to change from the normal intuitive establishment of disturbances in the temperature condition to a knowledge of deeper, more generalized and more differentiated principles were very likely radio engineers. The extreme complexity of electronic systems and apparatus, fraught with inadmissible reductions in their reliability and resources, caused a special interest on the part of these specialists in questions of prognosis and diagnosis of troubles. It is practically impossible to find the slightest degree of trouble in an intricate electronic circuit without effective diagnostic methods.

Since it is known that specific electrical parameters of radio parts (for example, these are the anode and cathode current, electrode voltages, magnitude and configuration of the signal on the cathode outlet and the like for tubes) change before the part burns out, electronic technicians attempt to track down changes in them. For this purpose, on their own and without complicated diagrams, they build supplementary alarm systems of a multitude of conductors, switches and other elements, as well as of special indicator and comparison devices. Naturally, it is impossible to encompass all parts by such a method. Usually, they test only the parameters of radio tubes and certain other less reliable elements. The bulk of the resistor, condenser, coil and relay types of parts are practically left to themselves.

Is it impossible to develop some sort of single, universal system for testing the operation of all elements, one by one, a system of predicting their failure and of quick indication of troubles? With all the incredible complexities of this problem, its solution has been achieved by a fairly simple method, at least in principle. The idea belongs to radio engineer S. I. Breslavskiy.

S. Breslavskiy proceeded from the fact that the operational capability of any element of electronic and radio circuits is determined by their thermal condition to a significant degree. It is precisely the heat phenomena which are most characteristic of, and most closely connected with, the breakdown of any radio parts. He reinforces this empirical principle, known to all radio engineers, with theoretical considerations.

Thus, the breakdown of any element is nothing other than a transition of a certain physical system from one steady state to another. Obviously, such a transition cannot take place without some additional expenditure of energy. In some cases the source of the input is the chemical energy of the substance included in the composition of one element or another, in others it is the electric power supply, and, finally, in still others, mechanical energy of outside origin (friction, vibration, a blow). Inasmuch as this is an irreversible process in the overwhelming majority of failures, an irreversible energy conversion must take place without fail. From the point of view of thermodynamics, it is an irreversible transfer of energy into heat. From this, a conclusion can be drawn of the inevitability of heat phenomena as the sole guides to failures.

Generally speaking, radio engineers have long used thermal phenomena for locating troubles. By rule of thumb, they look for scorched resistors and contacts. They test tubes, coils and transformers by feel. But it is almost too late, and a suspicious element, cooling off, does not betray itself externally in any way.

How can searching be improved? Obviously, the so-called heat indicator pigments, changing color at strictly defined temperatures, need to be used. The maximum permissible heating temperature is specified for each type of part and element, after which they are painted with the corresponding heat indicator pigment. The operator needs only to notice elements changing their color in a routine inspection of an apparatus. In order to avoid changing intact parts, subjected only to short-time heating, it is advisable to use reversible heat indicator pigments, which take on their initial colors again after a certain time which is sufficient for detecting suspicious points.

Opportunely, there already exist now fairly many heat indicator pigments intended for a wide range of operating temperatures. In particular, certain specimens of them were developed at the Rassudovoy N. Mendeleyev Moscow Chemical-Technological Institute. Thus, there are a light pink paint up to 75°C, bright blue up to 110°C, a green up to 85°C, a light brown up to 145°C, a yellow up to 110°C, an orange up to 155°C, a lilac up to 170°C and so forth.

Parts are best painted right during their production, and paint resources must correspond to part resources. Normally, an effort is made to obtain paint with a stable critical temperature, but it is still more tempting to obtain those paints which change their color with time, as the permissible heating temperature of parts changes because of the process of aging. Unfortunately, similar problems have been weakly worked out by chemists.

Inasmuch as heat indicator paints based on various critical temperatures have different colors, and, for purely constructive reasons, it is more convenient to use varicolored parts, a new difficulty arises in diagnosis of damages. How are just those parts which have changed their color by overheating to be separated from the color chaos formed? But again, there is an extremely simple and witty solution to the problem of simplifying the diagnosis. Parts are painted in "zebra stripes," in which one stripe is made in the normal manner, and the neighboring one with heat indicator paint. In the normal condition, the part appears to be a uniform color, but if it begins to overheat, it immediately becomes striped. It is not difficult to find the striped part among the uniform colored ones in a routine inspection.

We have spoken of overheating up to now. However, breakdowns are sometimes accompanied by, not only heat, but by characteristic electromagnetic radiations. Evidently, indicator colors which have selective sensitivity could be selected for them.

Composite coverings which change their colors in steps due to the temperature difference between the part and the surrounding medium, and not from temperature, are promising for purposes of diagnostics and predictions of damage. This difference precisely characterizes the operational capability of a part, and subsequently it does not depend on the surrounding air. There still are neither selective nor gradient heat indicators today. But they can be created by using the resonance properties of molecules and crystals, the selective capabilities of phosphors, or the onset of electromotive forces or ion migrations in dry electrolytes under the action of a temperature difference.

However, not only imaginative measuring techniques are needed for diagnostics of many general mechanical engineering assemblies. Frequently, it is only necessary to record a fairly large deviation from the temperature norms in time.

As an example, let us take a journal box, the weakest place on a railroad car to date. A whole army of inspectors checks the boxes at stops and, all the same, it will happen that they overheat, causing accidents and fires.

A basic deficiency of the traditional diagnostics is that inspection at a station does not always permit location of dangerous symptoms, since a box overheating en route may have had time to cool down at the moment of inspection. Obviously, diagnosis on the move would be the most reliable.

Temperature sensors can be installed on each box, and the readings could be transmitted by wires to the engineer's cab.

However, such a "head-on" solution would prove to be excessively expensive. Equipping of rolling stock would require millions of sensors and thousands of kilometers of wire, to say nothing of the periodic inspection of countless numbers of outfits.

It is more rational by far to do differently. Inspection apparatus which would detect overheating of a box and transmit information to the assistant stationmaster needs to be installed on the approaches to railway terminals. Such a remote diagnostic apparatus is widely used now on railways. In particular, one of the first efficient devices of such a nature (a recorder of hot boxes on a moving train) was built several years ago by a radio club in the city of Baranovichi.

The apparatus permits receiving of data, recorded on tape, of the presence of overheated boxes on trains moving at speeds of up to 120 km/hr. It notes just which box on which axle is overheated, counting from the head of the train.

The recording apparatus consists of two infrared radiation receivers, an axle calculating unit, two four-cascade, narrow-band, low-frequency amplifiers, a low-frequency oscillation generator which feeds the infrared radiation receivers, a recording and signaling unit, a power pack and an automatic unit for switching the instrument on and off.

Photoresistors or bolometers, installed at the foci of spherical mirrors, serve as infrared radiation receivers. To increase their sensitivity, the receivers are connected on opposite arms of a resistance bridge, supplied with alternating current from the generator. Two identical resistors, shielded from the action of infrared radiation entering from overheated boxes, but not shielded from the action of the outside temperature, are connected to two other arms of the bridge. They serve as a self-balancing bridge during air temperature fluctuations.

When a hot box goes past the receivers, the resistors change their resistance under the influence of the infrared radiation, which leads to an imbalance of the bridge. Low frequency oscillations are transmitted from there to the amplifier input, the signal level depending on the temperature of the box. If it is higher than permissible, it trips the recording mechanism.

The axle tabulation unit consists of a sensor, which is a transformer type induction converter, a one-cascade, low-frequency amplifier and a thyatron relay, which activates the tape feed mechanism.

A three-pronged cable strand with an open magnetic circuit serves as the wheel tabulator sensor. There are two windings on the cable. The primary is switched into the low frequency oscillation generator and the secondary to the amplifier input. The sensor is installed on the inside

of the rail in such a manner that a wheel passing by it closes the transformer magnetic circuit. At this moment, a sharp increase in alternating current voltage amplitude passes through the secondary winding. The amplified impulse challenges the action of the tape feed mechanism at one point and simultaneously makes a mark of the passage of the pair of wheels on the tape.

The recording and signaling unit consists of a recording mechanism, the pen of which (if there is no overheated box) traces a straight line on the tape. If the right or left box is abnormally heated, the pen makes a rejection mark to the right or left of the axle passage mark on the tape.

The apparatus is powered by a storage battery, the switching unit of which is installed at some distance from the recorder, and a passing train serves as an automatic power switch. The sensor of this unit is also installed on the rails, but at a distance of 500-600 m from the instrument itself. The sensor operates a relay, which turns on the recorder power, at the moment the first wheel passes by it. The switch-off unit operates similarly.

The automatic thermodiagnostic apparatus permits prevention of journal box breakdown and permits repair personnel to be informed, even before the train arrives, precisely how many boxes require immediate inspection.

#### Aromatic Diagnostics

The method of machine and mechanism diagnostics by odor stands somewhat apart from the others. It must be said that the sense of smell has undeservingly had little technical application up to now. Meanwhile, this is an obvious underestimation, because the olfactory "communications channel" is characterized by a relatively high capacity and resolving power. We easily distinguish the odors of the sea, sausages and lilacs. Even in one category, such as "smoke," we can easily discriminate between wood smoke, cigarette smoke, burning rubber, a samovar, kerosene, gasoline, coal and so forth. Experienced perfumers distinguish so many imperceptible shades of fragrances, that the total number of them probably amounts to tens of millions. Calculations show that humans are able to perceive on the order of 100 units of information per second by use of odors. This corresponds to approximately 30 letters and is close to reading speed.

In principle, "aromatic diagnostics" is used fairly widely. Thus, the odors of burning and of charred insulation give highly specific information to a repair man-electrician, and the odor of gas or gasoline, signifying a leak, immediately alerts gas system workers or drivers. However, the examples enumerated are rather the exception than the rule, since the majority of breakdowns and accidents and, even more, cases of wear and tear are accompanied by no sort of odors in themselves.

Meanwhile, methods have already been developed which use differentiated combinations of specific odors and specific equipment defects. In particular, such a method was used by inventor A. Poshenko for diagnostics of drill bits and other rock breaking tools (Central Asian Scientific Research Institute of Geologic and Mineral Raw Materials).

Drillers are frequently faced with special diagnostic problems in drilling test wells. The fact is that the drilling process goes well only when abrasion of the instrument does not exceed a specific value. It is very difficult to determine the moment when the abrasion limit is reached. It is practically impossible to do this by means of calculations, because the axial load on the tool, the number of revolutions, and rock hardness are always changing. Direct observation by instruments placed hundreds of meters in the earth also is unsuccessful. Drillers come to depend on their work experience alone. For example, noting when the well becomes deeper too slowly, they give the command to raise the tool up. Here, it is frequently the case that the bit proves to be in running order, and that it simply encountered rock in its way. This kind of an idle raising reduces the mean rate of progress by approximately 20%.

Obviously, a method of reliable remote diagnosis of the condition of the tool is necessary here. Moreover, it is desirable to dispense with the traditional electronic apparatus and sensors, which are difficult to place in the limited and extremely dusty space of the well.

Under such conditions, the use of odors is the simplest constructive solution. Small holes were drilled between the teeth of the drill bit, and miniature aluminum cylinders, capsules with a highly odoriferous substance, were pressed into them. As soon as the bit operating in the well is abraded up to the limit, the capsule is penetrated, so that air coming out of the well immediately takes on a characteristic odor. It is the utmost in simplicity and reliability in a diagnostic method. The capsule takes up almost no space, does not have to be withdrawn or adjusted, and is not afraid of vibration, moisture or temperature change.

Concerning the odoriferous substance, ethylmercaptan, which is used in gas producers to impart an odor to natural gas, is now used. Ethylmercaptan is cheap, readily available and has a sharp odor which hits you in the nose.

The economic effect of aromatic diagnostics is very substantial. The cost of drilling per running meter, amounting to 30 rubles, is reduced by 20%. True, the method is suitable only for drilling with air scavenging, but geologic prospectors, seismic researchers and hydrologists drill about 3 million m of such wells in a year.

Of course, odors propagate more poorly in liquids. Therefore, the method described is not suitable for well drilling with flushing. However, it is not difficult to modify it accordingly, placing an ampule, not containing odoriferous ethylmercaptan, but a strong dye, in the drill bit. In wearing away, the bit or cutter opens a water inlet. The dye reacts

chemically with it and immediately colors the flush water. If thiocyanate is used in combination with copper salts, an emerald green color is obtained, and if with iron salts, a bright red color. The required concentration is absolutely insignificant, three parts of coloring substance to a million parts of water.

But let us return to odors. Drilling tool diagnostics is only the first timid step towards the use of aromas, but it is a step which discloses tempting possibilities.

As the experiments of R. Gestelend showed, even frogs distinguish approximately 250 odors. The number jumps to several millions for rabbits. The same applies to humans.

The human nose instantly recognizes complex chemical substances, in analysis of which experienced chemists require months of persistent work in the laboratory (the concentration of the odoriferous substance can be so insignificant that no instrument whatever could detect it). This is demonstrated by the ability of dogs to follow tracks and the ability of salmon to find their way thousands of kilometers to the spawning grounds by smell.

We do not know precisely how the nose and the brain recognize odors, although mankind has been interested in this question for thousands of years. Dozens of theories have been introduced (they now number about thirty), beginning with Lucretius, up to academician A. Ioffe, but not a one of them agrees completely with the results of experiments. However, the specific mechanism of odor perception does not have a definitive importance for many technical applications, diagnostics in particular.

Imagine that the parts of machine tools, automobiles and cranes which are the most subject to breakdown and wearing out are labeled with strong-smelling substances. This is not difficult to do by using minute capsules, microblisters, stripes or impregnated inserts. Since the nose is always ready to perceive an odor instantly, we immediately know of the approach of danger, that a part, for example, has reached the limits of wear. Such a diagnostic method is invaluable in power-driven lines and automated plants, where each adjustor has tens or even hundreds of units of equipment. Individual inspection of separate mechanisms is senseless under such conditions. Even a dog can be employed to watch a cutting tool or a part going out of order.

This is not as absurd as it seems on first glance. Canaries have long warned miners of dangerous accumulations of fire damp in the mines of Belgium. In many countries, dogs search by smell for leaks in oil and gas lines and find iron pyrites beds. The Americans are experimenting with flies, attempting to make them find, by odor, leakage in sections of hydraulic and fuel systems of rockets which are hard to get to.

The simplicity and advantages of the method become especially graphic if they are compared with the traditional method of checking for wear by means of radioactive isotopes. It is difficult even to imagine how many sensors and recording instruments would have to be installed in automated factories, and how much wire is required to tap their indications into centralized panels which are convenient to survey. And how many additional complications there will be with safety procedures, with a deactivation and repeated labeling of parts. All of these difficulties become superfluous here.

Chemists now have available a huge kit of odors, which can be used as alarms, and which are not only harmless to the health, but even pleasant. Odors still have another advantage from the engineering point of view. In distinction from electrical alarms, they spread without connections, regardless of whether the part being checked is located on the outside of a machine or hidden in the most difficult place to reach, whether it is immobile or rotates at a speed of several thousand revolutions per minute. In combination with the high information capability of the olfactory channel, these qualities disclose in principle new possibilities for the creation of reliable machines and automatic machines.

The sole drawback is that odors must be perceived, if not by a man, by some other living being. However, there has been a breakthrough here and now. More or less successful designs of "electronic noses," miniature odor indicators, have appeared abroad. Thus, the "General Electric" indicator, together with an analyzer unit, weighs 10 kg overall. Its sensitivity is eloquently characterized by this fact: it detects a human by odor at a distance of up to 300 m. The odor indicator is already used, for example, for detection of ships equipped with internal combustion engines at great distances. The exhaust gases are the source of the odor in this case.

Scientists of the Illinois Institute of Technology have developed a specialized diagnostic system. Its task is not to find defects, but to "smell out" a bomb, placed in a airplanes by evil men.

#### The Visual Search for Hard-to-get-at Defects

The pressure level in hydro or pneumatic systems is an essential indicator of well-being, from the point of view of trouble diagnostics. Oil pressure sensors in internal combustion engine lubricating systems, and manometers in main air lines of railroad trains have long been necessary elements in checking apparatus.

However, the question is on the direct checking of standardized parameters in the cases referred to. Diagnostics is characterized by use of indirect values. The system for tracking the integrity of the air screw of a helicopter, proposed by A. Borshchagovskiy, is an interesting example of such an indirect use of pressure measurements.

As is well known, safety in helicopter operation is determined mainly by the durability of its main rotor. In distinction from an airplane, a helicopter can always accomplish a landing with an inoperative motor, but only if the multi-meter blades of its main rotor, rotating due to the flow of the air stream in the autorotation mode of operation, remain intact. Diagnosis of the condition of the blade and timely exposure of developing trouble is an extremely complicated problem. Visual inspection, and even magnetic, ultrasound or luminescence defectoscopy, frequently prove to be ineffective, because the power elements of the blades, the longerons, are hidden beneath the outer shell for the most part. X-rays also are no way out of the position. The apparatus is cumbersome and awkward. There are frequent mistakes in deciphering the pictures. However, the main thing is that a crack may arise in the blades immediately after inspection, and the blades simply will not last until the next inspection.

Air is pumped into the inside of each blade by the method of A. Borshchagovskiy. Sensors built into the blade sense this pressure and continuously transmit data to an instrument in the pilot's cabin. Upon appearance of the most insignificant crack, whether as a consequence of fatigue or of dents, an air leak starts immediately and the pressure falls, making the instrument operate and warning the pilot of danger.

The method of A. Borshchagovskiy is based on observation of indirect values in this manner, although they are closely connected with the defects which interest us. Meanwhile, methods of direct observation of units about which there is apprehension, even if they are located in places which are accessible with difficulty, have been developed in recent years.

These methods are based on the principle of image transmission by light guides. Transparent steklonite, thousandths of a millimeter in diameter, is covered with a very thin film of glass with a low index of refraction. A light beam directed into it goes along the fiber, reflecting from its wall countless numbers of times and comes out at the opposite end. A bundle of a few thousand of such fibers, covered by an overall coating, is a light guide or, as it is also called, a light cable. The end of it is similar to the retina of an eye or to a television screen, inasmuch as the image transmitted by the light guide also is broken up into separate elements. While a black-and-white television image contains about 250 thousand elements, there are already light cables of millions of fibers. Naturally, their resolving power is very high. But the main advantage of a light guide is the fact that it can be bent at any angle and even tied in a knot. However, an image sent from one end safely reaches the other. This is why they are widely used in making various kinds of flexible probes, intended for indiscriminate searching for defects in the internal cavities of machines and engines. Obviously, in medicine only "indiscriminate" diagnostics is possible. Therefore, probes made of fibers are the sole means for visual examination of the walls of the esophagus, stomach and other internal organs, where it was impossible with the comparatively cumbersome optical probes of earlier types.

Foreign automobile firms are now testing the use of light guides for continuous checking for defects of all external lights of an automobile, directly from the driver's seat. Under heavy automobile traffic conditions, a burned out bulb in parking light or brake light might become the cause of an accident. Fine light wires take part of the light flux of each bulb being checked and guide it to inspection apertures right on the instrument panel. The absence of any mechanical or electrical device whatsoever insures 100% reliable inspection.

A combination of flexible light guides with stroboscopic illuminators substantially expands the possibilities of inspection. Continuous examination of deeply hidden, rapidly rotating assemblies and parts, investigation of the process of formation and development of microscopic fatigue cracks and recording them on photo paper or movie film becomes practicable without stopping the machine.

A colleague at the USSR Academy of Sciences Institute of Mechanics, R. Kubyak, invented a special instrument on this principle, which has already been successfully used in fatigue tests. A counterform block, of cemented ends of fiber light guides, is attached to the working part of the object being tested. The axes of their fibers are situated perpendicular to the surfaces of the microplatforms of the object. Inasmuch as the first object selected for testing was the crankshaft of a "Zaporozhets" engine, the counterform block was a collar encircling the neck of the shaft. The opposite ends of the fibers, on the other hand, were presented in a single plane and cemented together so that their mutual positions with respect to the positions in the counterform did not change. The rectangular screen of the ends of the light guides was obtained as a result, on which an image of the curvilinear surface of the working part (neck) of the crankshaft was projected. Illumination of the neck was accomplished with a stroboscopic illuminator, operating synchronously with the shaft load frequency, with the light being fed through the glass light guide. The light reflected from the neck through the same light guide was "transported" in the opposite direction to the screen. By changing the phase of the synchronization of the stroboscopic illuminator, an image of the working part of the object being tested can be obtained at any dynamic loading torque, for example, at the torque of the maximum opening or closing of fatigue cracks and so forth.

#### Acoustic Diagnostics of Damage

The world around us is full of audible and inaudible sounds. Their diversity is practically limitless. Birds babble, violins sing, winds howl, waterfalls roar, mountain landslides rumble, trees crack from frost, autos honk, leaves rustle, doors and ships' masts creak, hammers knock, bones crackle, cows moo, strings twang, children are noisy. Single verbs designating diverse sound phenomena can be counted by the dozens and even by hundreds. Each sequence of sounds constitutes its own kind of language. We have known certain languages for a long time and we use them widely, the language of human speech and the language of music. We have begun to study the "languages" of fish, monkeys, dolphins and other animals comparatively recently.

The conclusion can be reached by analogy of the existence of languages in which machines, systems of living organisms and technological processes "speak." These "languages" have their own dictionaries, alphabets and grammatical rules, but they have still been studied little. It is true that machines do not yet have their written language, but it can be created.

There is a basis for assuming that any aggregates of acoustic signals are only separate varieties of the generalized physico-mathematical language of nature. Knowing this language, we are able to use the engineering of sound widely in the most diverse areas of knowledge, and for diagnostics of damaged living and technological systems in particular.

The ability to visualize sound is an important step in acoustic diagnosis. The conversion of acoustic signals into visible images is very complicated at first glance. Nevertheless, every school boy encounters it several times a day. You see, ordinary letters and musical notation also signify visualized words or musical phrases. A burning candle can serve as the simplest physical instrument for visualization of sounds. Its flame is deflected differently by pronunciation of different vowels. However, a candle is a very crude instrument. For example, the sound "u" is recognized immediately by the trembling of the tongue of flame, but it is difficult to distinguish between "a" and "o." An oscillograph, drawing a curve on the screen, which characterizes change in the force of a sound with time, gives a more detailed image. The spectrograph provides a still more detailed one. It is an instrument consisting of several filters, with each adjusted to its own frequency. Signals go through the filters and enter a measuring instrument, which records their levels. In the end, we obtain a columnar graph on a cathode ray tube, the result of a spectral analysis of sound. Such a graph represents sound forms with sufficient completeness for many practical aims.

By the way, the now widely known light music, based on specific interrelationships between sound and light, also is one of the methods of visualizing sound.

The most highly perfected method of visualization today is the singular "apparatus for comparative identification of spectral forms," called by the first letters of the words of its English name, stseptron. The stseptron or fiber analyzer is, roughly speaking, a rectangular brush of fine glass fibers. Each fibril plays a double role in it. On the one hand, it is a tuning fork, a rod fastened on one end, capable of vibrating at the natural frequencies included in the alphabet of its basic tones and overtones, which it separates out from the wide spectrum of stimulations. On the other hand, it is a light guide, a wave guide, filtering visible light without noticeable attenuation. The rigidity of the fibrils can be changed by changing their length and diameter, and they can be tuned to different frequencies in this manner.

Basic light fiber brushes are connected to an electromechanical converter, to a piezoelectric plate or to a moveable coil of an electrodynamic system, to which an amplified microphone signal moves. In addition, a plane-parallel light beam shines from behind the ends of the fibers. Now,

if you look at the brush from the operating ends, you will see a rectangle of luminous points, the stseptron field. Actually, the luminous points are not visible. For convenience in analysis, all of the light guides are shielded by a point mask, a mask which covers the light. It is not difficult to make the mask. The light must be turned on and the luminous field of the stseptron photographed. The negative obtained is the shield. It is superimposed so that the dark spots exactly cover the light points. In this manner, when there is no sound the stseptron field remains dark.

But now some signal is heard. The resonant fibers respond immediately. Vibrating, the fiber "projects" through the shield, and a light point becomes visible. The light flash expands into a line at considerable amplitudes.

Considering the stseptron field as a mathematical matrix, composed of individual rows and elements, with the light point taken as "1," and the dark as "0," the complex sound signal, possessing a complex spectrum, possesses some distribution of units, light points, on the matrix. Photographing the matrix over short intervals of time, we obtain a series of frames, a sort of home movie of sound.

But, properly, why are all these simple and complex visualization methods needed? In the final analysis, for automatic discrimination of sound forms. Reducing sounds to images, we can take advantage of the methods of discrimination of visual forms developed by cyberneticists.

It must be said that the overall recognition problem is an extremely complicated piece of work. From the mathematical point of view it includes a probabilistic evaluation of a series of parameters, of indices included in N-dimensional space. A particular, simplified case, when it is necessary to identify some vowel, can be introduced as an example. The stseptronograms of all vowels are photographed first. Then, using their negatives as masks, the vowel being identified is pronounced in front of the stseptron. The mask which produces darkness or a minimum of light will characterize the sound pronounced. Such a simple method is unsuitable for machine or fish "languages," which do not have clear alphabets. This is all the more so in that, in the opinion of specialists in the theory of automatic sound form recognition, vocal signals are the most easily recognizable in principle. You see, the sounds of speech are the products of prolonged biological evolution. They are the result of the optimum utilization of ligaments, larynx, mouth cavity, speech, of all vocal data serving for the generation of articulate signals. It is clear that neither machines nor technological processes have undergone such evolution.

On the other hand, every person pronounces letters differently. In addition, even one person changes pronunciation each time, so that a sound, like a stream, in the well-known expression of Heraclites, can never sound the same twice.

Finally, there is still another difficulty. When a man speaks, we are convinced that his speech is more or less intelligent. But, do natural

sounds, the sounds of machines, perhaps contain no information at all? Are they a random collection of sounds, devoid of all sense? Sometimes, this is really so. However, there is sense in many cases, only we cannot always understand it.

It must be admitted that the majority of the difficulties referred to still have not been overcome. Nevertheless, even a partial solution of the problem has already given much to technology. Thus, there is already a device which recognizes individual words. Using language with a very limited vocabulary, information can be quickly introduced into a computer, and a set of orders can be given at a distance, by telephone, and so forth. Automatic writing machines, printing directly from the voice, synchronous automatic interpreters and so forth will appear in the future.

It is interesting that, while it is not yet possible to recognize the meaning of speech, spectrograms always permit precise voice identification, because the voice has in itself ineradicable signs of the personality of the speaker, like finger prints.

The American inventor, Lawrence Hirst, using this circumstance for crime investigation, tells how he and his colleagues attempted to outwit the machine. It was like a play. Whatever we did, shout, whisper, hold the nose, put stones in the mouth, the voice could always be recognized. The best imitators were invited. The prints invariably gave a pattern typical of the voice of the imitator, and not of the person whom he imitated.

The delicacy of acoustical methods permitted successful use of spectrograms for diagnosis of mental illnesses. Generally speaking, doctors have known for a long time that the voice of a mentally ill person is noticeably different from the voice of a healthy person. The volume and distinctness of pronunciation of words, the extent of pauses, expressiveness of speech and so forth receive attention here. Of course, all of this is approximate, rule of thumb. A multitude of new psychotropic preparations have appeared in recent years, and objective indices of the results are necessary for testing them. As tests have shown, spectral voice analysis produces outstanding results. The finest nuances in changes in a patient's condition are successfully detected, and such diagnostic symptoms as the most experienced psychiatrist is unable to notice are noted successfully by using it. The voice becomes an authentic "mirror of the mind," reflecting all shadings of higher nervous activity. Moreover, spectrograms are easily united with the history of the disease, in this manner accumulating much statistical material.

Similar possibilities are disclosed in automatic analysis of medical sounds of the lungs, heart and vessels. The results of analysis, introduced into a computer, together with other data, permit creation of reliable automatic diagnostic machines.

Two more acoustic instruments, which have already come into use in medical practice, and which are very similar to industrial defectoscopes

in operating principle, can be referred to. One instrument detects diseases of the knee joints by crepitus, and the other is for examination of the middle ear. In the latter case, a small jet of air is blown through the Eustachian tube and the apparatus analyzes the noise produced.

As for machines, it is perfectly obvious that sound diagnosis methods can be applied to them. Strictly speaking, this was done long ago. Not a single driver will go any further when he hears some suspicious noise or knock in the motor. However, while the ears hear only distinct deviations from the norms, an instrument in working order separates individual components, each "singing" at its own frequency, from the general chorus of voices, and accurately records that there is a crumbled tooth on such and such a gear, that such and such a bearing is overheating, that a dent has appeared in such and such a ball and so forth. In particular, an instrument of this sort for diagnosis of tractors has been built in the cybernetic laboratories of the All-Union Scientific Research Institute for Mechanization of Agriculture. The instrument is combined with a computer and an automatic typewriter, so that the diagnosis is issued in the form of a common typewritten text, which does not need deciphering. The text reports the number of the damaged part, possible further service life and the optimum method of repair.

A logical development of such instruments leads to automatic acoustical supervision of the operation of entire plants and continuous lines. In distinction from all other methods of supervision, here, wires do not need to be stretched out to each machine or part nor do thousands of sensors have to be installed. It is sufficient to have a microphone and recognition device in place of them.

Crackling of solid rock masses and coal beds always indicate the formation of cracks. However, it is necessary to distinguish industrial noises, for example, from pneumatic drills, and noises warning of a threatening landslide. Observers, trained for many years, are now required for this. As recognition systems develop, they, too, will be replaced by automatic machines.

Many other practical applications, which already are or will be possible, on the basis of automatic sound form recognition, could be described. They include prediction of storms, earthquakes and tsunamis, determination of the kind of fuel flowing through a hermetically sealed pipeline, production quality control and so on and so forth.

However, let us return to acoustical diagnostics proper. An instrument for inspection of ball bearings can serve as a concrete example, which demonstrates the effectiveness of its methods.

The fact is that bearings rarely get out of order without acoustical, noisy symptoms of impending trouble. However, these symptoms sometimes remain unnoticed, because of the absence of perfected diagnostic instruments. The best such instrument up to this time has been the ear of an experienced inspector.

Not long ago, the well-known Swedish SKF Company, which has produced bearings for several decades, developed an electronic device to measure impact, "knock," in bearings. It proved to be so sensitive to the very earliest symptoms of impending defects, that the firm seriously considers stopping the sale of bearings and of converting to leasing them with guaranteed regular technical maintenance and replacement of parts which are near to getting out of order.

The Stockholm engineer, S'yegol, is the inventor of the new inspection device. In studying the operation of bearings, he observed that an approaching fatigue breakdown was always accompanied by chipping or flaking of metal, either from the surface of the bearing race or from the balls or rollers. When balls and rollers are flattened at a damaged spot, mechanical jerkings cause brief high-frequency oscillations, which are transmitted to the bearing housing. The oscillations are detected by a device which is, in point of fact, a portable accelerometer. It is connected to the bearing by a mechanical device in the form of a wire inserted into a connection on the bearing housing.

Shock waves are transmitted to the apparatus by the connecting wire, which produces a signal proportional to the force of the mechanical blow. All oscillations from external sources of vibration are filtered out by a band filter. This is practical because the maximum frequency of ordinary mechanical vibrations does not exceed 30 khz, while shock waves arising from a bearing defect can have frequencies up to 50 khz, and sometimes higher.

The reading is produced on an indicator with a logarithmic scale, numbered from 0 to 10,000. Inspection is carried out by comparison of an instrument reading obtained in the laboratory on bearings of various dimensions with known defects, which have different speeds of rotation, with results obtained during operations under field conditions.

The instrument is provided with a potentiometer, which sorts out all shock impulses which exceed a specified level. The impulses are amplified, so that the technician can inspect the bearing by ear. He can precisely establish the location of the defect by the differences in amplitude of shock impulses, and can replace, not the entire bearing, but only the defective ring or ball. To a certain extent, the method is similar to the usual listening by use of the simplest "stethoscope," a wooden stick. But the stick can be successfully used only by people with very acute hearing.

The instrument is no bigger than a shoe box in dimensions. It provides for inspection of approximately 300 bearings a day.

The Soviet inventor-aviators A. Yeroshkin, P. Ormanov, Ye. Samylin and V. Maksimov are considering diagnostics of damage to ball bearings somewhat differently. Their approach is characterized by particularly high reliability requirements for the diagnostic method. This is understandable. Ill-timed discovery of a defect in a jet engine ball bearing can quite possibly entail an aircraft accident. Defects in bearings must be discovered

as early as possible, before their progressive development leads to secondary damage and destruction of other assemblies and parts.

However, known methods of diagnostics, based on discovery of chips in oil, on changes of electrical resistance in bearings and on its vibro-acoustic characteristics, do not provide for meeting the requirements referred to.

Actually, chips are detected in oil by periodic examination of oil filters and magnetic plugs, which are installed in main oil lines and which trap chips, or by detection of changes in the chemical and physical characteristics of the oil by means of periodic chemical or spectrographic analyses of samples of it.

However, chips can often get into the oil of machines and mechanisms as a result of insufficiently thorough rinsing and cleaning of parts or as a consequence of the normal course of running them in. Moreover, inspection of the filters requires their periodic removal and frequently does not provide a reliable indication of the beginning of the appearance of a defect. Magnetic plugs trap chips only of ferromagnetic materials and are periodically examined also. In this manner, only a conjectural judgement as to bearing damage or a discovery of it at a considerably advanced stage can be made by metallic chips discovered in the oil.

As to the appearance of changes in the chemical or physical characteristics of the oil, it involves comparatively complicated laboratory analyses and, besides, requires periodic removal of samples from the oil system.

Investigation of vibroacoustic characteristics or electrical resistance of bearings is impossible without complicated electronic apparatus and highly qualified investigators.

The method of Yeroshkin, Ormanov, Samylin and Maksimov is based on direct, continuous or periodic strain gauge measuring of the bearing rings or of special elastic elements while the machine is operating. Changes with time in the amplitude of the maximum bending torques of the rings or elastic elements indicate a nascent defect. If a bearing is in working order, the oscillogram of the wire strain sensor cemented to its ring will be a strictly periodic curve, reflecting the expression of changes in strain on the ring during movement of the balls along it. If the slightest defect appears, the periodicity of the signals immediately is disturbed and signals of sharply increased amplitude arise, which correspond to the appearance of shock stresses. Amplitude surges have a random nature, with incidental signals of a sharply decreased amplitude also appearing.

The mechanism described clearly traces the operation of a bearing in any mode of operation, and does not depend on either rotation speed or loading. Signals leaving the strain sensors are easily analyzed, either visually on a cathode ray oscillograph or by oscillograms recorded on a loop oscillograph.

Tests have confirmed the extreme sensitivity of the method. When bearings of an operating machine begin to change to an oil deficiency mode of operation, the form of the curves immediately changes, recording the slightest damage to the bearings.

There is another method of diagnosing bearing damage, this time not to ball bearings, but to roller bearings, developed for seagoing vessels. It is well known that the safety of a ship's voyage depends to a considerable extent on reliable operation of the drive shaft and main engine shaft bearings of the ship. This reliability is, in turn, connected with the ensuring of the proper friction conditions in the bearings. The transition from liquid friction to semidry or dry is the first symptom of an approaching breakdown and, then, an emergency stop of the vessel in the open sea and so forth. Therefore, the best method of diagnosis, rather, prognosis of the probability of damage is to find some breakdown prevention signal methods.

Until recently, the basic method for checking such parts was an occasional check of the heat of the outer surfaces of bearings. True, still another method was known, based on changes in electrical capacity of the oil layer of an insulated shaft, but it was not suitable for ships, for the drive shaft is connected to the ship's hull through the water.

Remote temperature inspection of drive shaft bearing supports, which has received some distribution recently, also was not sufficiently complete, since it did not permit monitoring such damage as cooling water getting into the bearings or oil leaking from them.

A witty and extremely reliable method of preventive diagnosis was suggested recently by the Soviet inventor V. Guzeyev. The method was based on the fact that, in a disruption of the oil film in a bearing, the electrical resistance immediately falls in a gigantic electrochemical "battery" circuit, consisting of sea water and two electrodes, the propeller and the hull. Well, the propeller and the steel shell of the hull are made of different metals and have different electrical potentials. Being immersed in salty sea water, which is the electrolyte in this case, they form an electrochemical pair and a definite potential difference arises between them.

Under normal operating conditions of the engine assembly of the vessel, the electrical circuit is broken by a layer of oil in the drive shaft bearings. The electrical resistance between the drive shaft support journals and the surface of the bearings is high, so that the voltage between the rotating drive shaft and the ship's hull, measured with a voltmeter, has a substantial value. In steel ships with brass or bronze propellers, it reaches up to 300-370 mv.

As soon as the oil film is broken, even if only on one drive shaft bearing connected to the propeller, the resistance falls sharply. A current of up to 20 amp arises in the electrical circuit of the propeller-shaft-bearing-hull. The voltage between the drive shaft also falls and, depending on the degree of disruption of the oil film on the bearings, can decrease almost to zero.

In this manner, a voltage drop between the drive shaft and the hull is the diagnostic symptom which indicated the appearance of dry or semidry friction in the drive shaft bearings.

Another advantage of the symptom mentioned consists of the fact that it gives knowledge of other characteristic troubles, such as misalignment of the packing, the entry of foreign particles or impurities into the lubricant, leakage of oil from the bearings below the permissible level, cooling intake water getting into the lubricant and so forth. It permits prevention of accidents connected with the winding of the steel tow line around the propeller, since, in this case, the voltage falls to zero.

The diagnostic method described was tested during the voyage of the steamship "Bobruyskles" from the Baltic to South American ports and back to the Baltic. When everything was in order, the electrical voltage between the ship's propeller and hull fluctuated somewhere around 300 mv. But then, in the Atlantic Ocean, one of the bearings became misaligned. The voltage immediately fell to 30-100 mv. The fault was corrected and the voltage climbed to the former level. After four days, a refrigerant line leaked and water got into the oil of another bearing. The voltage fell at once to 80 mv.

In this manner, diagnostics according to the voltage value completely justified itself. It instantly signalled trouble and, thereby, freed attendants from periodic checking of the bearing conditions.

#### Conclusion

In a small booklet, it is impossible to characterize even briefly the extremely diverse methods of machine diagnostics. We have referred neither to introsopic methods, developed under the direction of Doctor of Technical Sciences P. K. Oshchepkov, nor of the radioisotope methods, which have undergone great development due to the work of scientists of the Bauman Moscow Technical College, nor of the vibration methods, investigated at the State Institute of Machinery Science, which permits diagnosis of practically every part of a complex automatic lathe on an oscillogram by movement of one element, and so forth. These and each of the methods enumerated have their own varieties, calculated specifically for concrete diagnostic objectives.

The author hopes, however, that even this far from complete information which has found a place for itself in the booklet, will give readers at least an approximate conception of this promising, dynamically developing field of knowledge.

## Table of Contents

	Page
Foreword . . . . .	1
Diagnostics of Strength and Deformability of Materials and Machine Parts . . . . .	2
Diagnostic Modeling . . . . .	12
Contact Stresses and Plastic Deformations . . . . .	14
Thermal Indication of Trouble . . . . .	21
Aromatic Diagnostics . . . . .	25
The Visual Search for Hard-to-get-at Defects . . . . .	28
Acoustic Diagnostics of Damage . . . . .	30
Conclusions . . . . .	38